9.1 Cabling

Grid-connected PV systems require both DC and AC cabling to connect the relevant components together. DC and AC cables are specifically designed for the electrical characteristics of their respective form of electricity and should not be interchanged.

The **DC cables** found in a grid-connected PV system are (Section 9.1.1):

- ***PV module cables:*** These are typically pre-connected to the module and connect a set of PV modules in series, forming a string.
- ***PV string cables:*** These connect a string of modules to the PV string combiner box.
- ***PV sub-array cables:*** In larger systems, these connect the PV string combiner box to the PV array combiner box.
- ***PV array cables:*** These connect the PV string combiner box (or the PV array combiner box in larger systems) to the PV array DC disconnectors.
- ***Inverter DC cables:*** These connect the PV array DC disconnectors to the DC side of the inverter. This cabling may also be referred to as PV array cabling, but it has been separated in this publication to provide an extra description.

The **AC cables** (Section 9.1.2) found in a grid-connected PV system are AC supply cables. These connect the inverter to the inverter AC disconnector (at the inverter, if necessary) and then to the point of connection to the grid (the PV array main switch) in the switchboard.

The array's **earthing cables** are also an important part of a grid-connected PV system. They are needed to protect both the system equipment and people from dangerous fault conditions, and may be required for the operation of some systems. As earthing is part of a system's protection, it is covered in Section 9.2.

Details of how to correctly select and size the cables in a grid-connected PV system are covered in Chapter 14.

9.1.1 DC Cables

DC cables are used between the PV modules and the DC side of the inverter.

It is important to ensure that the DC cabling used is correctly labelled in accordance with applicable standards.

Module Cables

Modules usually come with a positive and a negative cable hardwired into the module's junction box at the back of the module. These are used to connect the modules together to form a string. Each pairing of cables has a male and a female connector (or 'plug') to wire modules together quickly and safely (see interconnections section below). The cable and plugs can also be individually purchased so that the module cable lengths can be adjusted to suit a particular installation. Module cable sizes are typically 4 mm^2.

String, Sub-Array, Array and Inverter DC Cables

String cables connect the strings of modules to the PV string combiner box. In larger systems, sub-array cables are used to connect the PV string combiner box to the PV array combiner box. Array cables are used to connect the PV string combiner box (or the PV array combiner box in larger systems) to the PV array DC disconnectors. Finally, DC cables are used between the PV array DC disconnectors and the inverter.

AUSTRALIAN STANDARDS

AS/NZS 5033:2014 Clause 4.3.7 states that:

- All connector pairings must be of the same type and from the same manufacturer
- Cables used within the PV array shall be:
- UV-resistant (if exposed to the environment)
- Rated to the overcurrent protection device, or maximum normal operating current
- Flexible, to allow for movement of the cable
- Single core, double insulated.

According to ***AS/NZS 5033:2014***, all cables used for the PV array must meet PV1-F requirements, UL 4703, or VDE-AR-E 2283-4.

13.3 DC Disconnection Devices

Disconnection devices allow parts of the system to be electrically isolated. DC disconnection devices can be split into two categories:

1. Load-breaking, where they can be disconnected when current is flowing through them; these devices are switch-disconnectors or circuit breakers, although the term 'isolators' is used for simplicity in labelling.
2. Non-load-breaking, where they can be disconnected only when there is no current flowing through them.

Disconnection devices may be required at the string, sub-array and/or array level of a grid-connected PV system. For all levels of disconnection, the device used should have no live parts exposed at any time, regardless of whether the device is switched on or off. It also must comply with any other requirements set by the appropriate standards and guidelines.

The disconnection device may be combined with the overcurrent protection in the form of a DC circuit breaker. If this is done, a suitable circuit breaker must be selected. According to the latest standards, circuit breakers must be non-polarised. It can be advantageous to install a non-polarised circuit breaker (or other appropriate easy to operate device) on each string for easier maintenance and fault-finding.

13.3.1 String Disconnection

String disconnection enables each string of the PV array to be electrically isolated from the other strings and the rest of the PV system.

Requirements of String Disconnection Devices

For both LV (120–1,500 V DC) and ELV (<120 V DC) systems, it is recommended that the string cable has a form of non-load-breaking disconnection.

Sizing the String Disconnection Devices

The required sizing of string disconnection devices is as follows:

- Rated for PV array maximum voltage.
- Have a current rating greater than or equal to the string overcurrent protection present. If a string overcurrent protection device is not present, the disconnection device must have a minimum rating of the CCC of the string cable.

Installation of String Disconnection Devices

Non-load-breaking disconnection is usually provided by module manufacturers in the form of plug-and-socket connectors. If circuit breakers are used as the overcurrent protection and means of disconnection, these would be installed in the string combiner box.

EXAMPLE

An array has 12 modules set up in two parallel strings of 6 modules, with V_{OC} of 39.2 V, γ_{VOC} of −0.33%/°C and I_{SC} of 7.4 A. Calculate the PV array maximum voltage for this array, given that the site's lowest expected temperature is 5°C.

Since there are 6 modules in each string and voltage is the same in parallel strings, the PV array maximum voltage is:

$$\begin{aligned} V_{MAX\_OC\_ARRAY} &= V_{OC\_ARRAY} + \gamma_{OC} \times (T_{MIN} - T_{STC}) \times N_S \\ &= (39.2\ \text{V} \times 6) + (-0.0033/°\text{C} \times 39.2\ \text{V}) \times (5°\text{C} - 25°\text{C})] \times 6 \\ &= 235.2\ \text{V} + 0.1294\ \text{V}/°\text{C} \times 20°\text{C} \times 6 \\ &= 250.7\ \text{V} \end{aligned}$$

AUSTRALIAN STANDARDS

AS/NZS 5033:2014 Clause 1.4.13 defines the term disconnector, and Clause 4.3.5 covers the requirements for DC disconnection devices.

AS/NZS 3000:2018 states that load-breaking switches should be lockable in the off position.

IMPORTANT!

Disconnection devices do not switch off during fault conditions.

Circuit breakers can be used to provide overcurrent protection and disconnection, so that they switch off during fault conditions.

If separate overcurrent protection is present, the disconnection device must have the same current rating: otherwise it may be damaged by overcurrent.

AUSTRALIAN STANDARDS

According to ***AS/NZS 5033:2014*** Clause 4.2, the PV array maximum voltage is calculated using:

$$\mathbf{V_{MAX\_OC\_ARRAY} = V_{OC\_ARRAY} + \gamma_{OC} \times (T_{MIN} - T_{STC}) \times N_S}$$

Where:

- $V_{MAX\_OC\_ARRAY}$ = PV array maximum voltage (in V)
- V_{OC_ARRAY} = PV array open circuit voltage at standard test conditions (in V)
- γ_{OC} = Negative temperature coefficient of V_{OC} per degree Celsius (in V/°C)
- T_{MIN} = Minimum cell temperature (in °C)
- T_{STC} = Cell temperature at standard test conditions (constant of 25°C)
- N_S = Number of modules in series

If the module temperature coefficient is not available, ***AS/NZS 5033:2014*** Table 4.1 contains some universal coefficients that can be used.

13.3.2 Sub-array Disconnection

Sub-array disconnection enables each sub-array of the PV array to be electrically isolated from the other sub-arrays and the rest of the PV system.

Requirements of Sub-array Disconnection Devices

For LV and ELV systems, each sub-array cable is required to have a disconnection device for isolation. This device does not have to be load-breaking. Systems with sub-arrays are generally large: a load-breaking disconnection device could be advantageous as an additional safety feature for large, LV systems. Should a load-breaking disconnection device be chosen, it must be non-polarised and able to isolate all active conductors simultaneously.

Sizing the Sub-array Disconnection Devices

Sizing of the sub-array disconnection devices is required to be as follows:

- Rated for PV array maximum voltage.
- Have a current rating greater than or equal to the sub-array overcurrent protection present. If a sub-array overcurrent protection device is not present, the disconnection device must have a minimum rating of the CCC of the sub-array cable.

Installation of Sub-array Disconnection Devices

The module's plug–and-socket connectors will act as the non-load-breaking disconnection of sub-arrays. If circuit breakers are used as the overcurrent protection and means of disconnection, these would be installed in the string combiner box.

13.3.3 Array DC Disconnection

A load-breaking device for disconnecting the PV array on the DC side of the inverter is essential for safety in grid-connected PV systems. Two DC disconnectors may be required: one adjacent to the array and one adjacent to the inverter (see 'Installation of Array DC Disconnectors' below).

Requirements of PV Array DC Disconnectors

For all systems, the PV array DC isolators must be readily available load-breaking disconnection devices and lockable in the 'off' position. They must be non-polarised and able to isolate both positive and negative active conductors simultaneously under load.

A non-polarised circuit breaker can be used as the readily available load-breaking disconnection device.

If micro-inverters are used, an array DC disconnector may not be required. The relevant standards should always be referenced when determining disconnector requirements.

AUSTRALIAN STANDARDS

AS/NZS 5033:2014 Clause 4.3.12 outlines installation requirements applicable to micro-inverters.

Selection of the PV Array DC Disconnectors

The relevant Australian standards contain specific requirements for the array disconnection device, known as the PV Array DC Isolator. The requirements may differ for sizing and installing a PV array DC isolator that is integrated into the inverter. It is important to refer to the inverter manufacturer or installation manual to determine whether an in-built isolator is suitable for the system. An additional external isolator will be required if the in-built isolator does not meet all the requirements.

To check whether switch-disconnector is suitable for a system, perform the three steps below while referring to the isolator's datasheet. For these calculations, the maximum current is defined as $1.25 \times I_{SC}$ ARRAY .

Step 1: Thermal effects

The maximum current must be less than or equal to Ithe for the installation conditions:

- Indoors at 40°C ambient for isolators installed indoors.
- Outdoors at 40°C ambient for isolators installed outdoors in a location fully shaded all day (e.g. carport, verandah).
- Outdoors at 60°C ambient with solar effects for rooftop isolators or isolators
- installed externally where the enclosure or shroud will receive direct sunlight.

Step 2: Operational conditions

Consider the isolator configuration when the positive and negative conductors are operating in series. Looking at the first row where U_e is higher than the PV array max voltage, check that I_e is higher than the maximum current.

Step 3: Fault conditions

This step is for non-separated (transformerless) inverters only. Considering the isolator configuration when the positive and negative conductors are not working in series (e.g. due to an earth fault on one of the conductors), check that I_{make} and I_c (break) are higher than your maximum current for the maximum voltage U_e.

When in fault conditions, the isolator must be able to withstand the maximum current using half of the poles (either the negative or the positive side only). The Imake and I_c (break) is the current that one pole can withstand for very short periods of time. The isolator should be replaced after breaking this current.

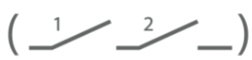
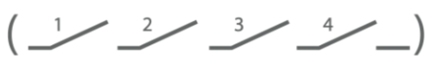
AUSTRALIAN STANDARDS

AS/NZS 5033:2014 Appendix B2 outlines DC disconnector voltage rating requirements, in addition to the operation of the array disconnector with normal and single earth fault conditions.

EXAMPLE

The switch-disconnector with specifications given in the datasheet below will be used as the rooftop PV array isolator for an array with a transformerless inverter. The system has a PV array maximum voltage of 840 V and an array short circuit current of 17 A. The following example checks whether the isolator selected is suitable for this purpose.

Identification	Rating Data
I_{th} rated thermal current, unenclosed, at 40°C shade ambient air temperature	32 A
I_{the} rated thermal current, indoors, at 40°C shade ambient air temperature, in a specific dedicated enclosure	32 A
I_{the} rated thermal current outdoors at 40°C shade ambient air temperature without solar effects in a specific dedicated enclosure rated IP 56NW	32 A
I_{the} *solar* current value, outdoors at 60°C shade ambient air temperature, with solar effects in a specific dedicated enclosure rated IP 56NW	28 A

	U_e rated operational voltage (V)	I_e DC-PV2 rated operational current (A)	$I_{(make)}$ and $I_{c(break)}$ DC-PV2 $4 \times I_e$ (A)
2 pole 	≤500	32	128
	600	32	128
	800	27	108
	1000	13	52
4 pole 	≤500	32	128
	600	32	128
	800	32	128
	1000	32	128

Example datasheet from an isolator manufacturer. Values will differ for different brands and models.

Step 1

$1.25 \times I_{SC\_ARRAY} = 1.25 \times 17$ A = 21.25 A. This isolator will be installed outdoors in direct sunlight. I_{the} under these conditions is 28 A according to the datasheet, which is higher than 21.25 A, so the rating is acceptable.

Step 2

The isolator has four poles and there is only one string to be switched, so the positive and negative conductors will each go through 2 poles (see diagram on the next page). During normal operation, these operate in series, so there are 4 poles total operating in series. Looking at the 4 pole configuration in the datasheet, the next highest U_e above 840 V is 1000 V, and the corresponding I_e is 32 A. This is higher than 21.25 A, so the rating is acceptable.

AUSTRALIAN STANDARDS

AS/NZS 5033:2014 Clause 4.4.1.2 outlines the requirements for when inverters with multiple inputs need to be removed for repairs or replacement.

The array DC disconnectors can be integrated into the inverter as long as they are designed to remain operational when the rest of the inverter is removed (i.e. they stay behind). Otherwise, separate disconnectors should be installed.

Installation of Array DC Disconnectors

The location of the PV array DC disconnectors may vary depending on the applicable standards. The general rule is that there needs to be a disconnection device adjacent to the array (micro-inverters may be the exception), and in many cases there also needs to be one adjacent to the inverter, unless the inverter is within 3 metres and in line of sight of the array.

EXAMPLE

In Australia, according to ***AS/NZS 5033:2014*** Clause 4.4.1.4, the PV array DC isolator must be installed adjacent to the PV array. If the inverter is more than 3 metres away or not in line of sight of the array, another PV array DC isolator must be installed adjacent to the inverter.

In New Zealand, according to ***AS/NZS 5033:2014*** Clause 4.4.1.4, a PV array DC isolator does not need to be installed adjacent to the PV array provided certain conditions are met, including having a PV array DC isolator installed at the inverter.

AUSTRALIAN STANDARDS

For more information on the DC disconnection device requirements in Australia, including isolator installation and removal, consult ***AS/NZS 5033:2014*** Clause 4.4.

DC Disconnection for Inverters with Multiple Inputs

Inverters with multiple inputs connect the strings together within the inverter. This configuration determines the array disconnection device requirements, as there is no external array cable on which to install the array disconnection device. Therefore, a PV array DC isolator must be installed on each string, regardless of whether the strings are connected to a single MPPT or individual MPPTs.

Some inverters with multiple inputs are supplied with a DC disconnection switch that isolates all of the strings at once. Care must be taken that this disconnection switch meets all relevant standards and guidelines.

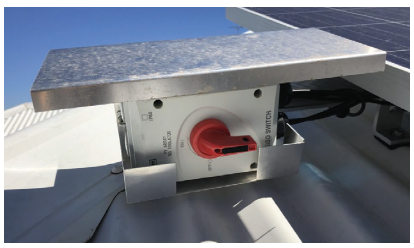
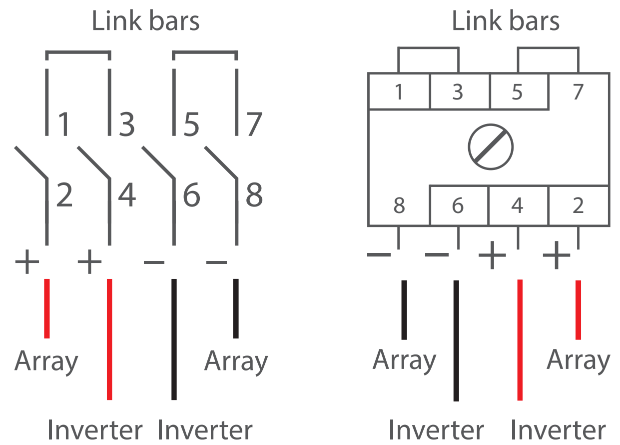


Figure 13.10: Isolator installed with shroud.

PV array DC switch-disconnectors must:

- Comply with ***AS 60947.3***
- Be supplied with dedicated individual enclosures rated at least IP56NW if installed outdoors, to ensure that water jets and rain will not enter the enclosure.
- Have utilization category DC-PV2.
- Rooftop isolators must be installed with a shroud to protect against rain and direct sunlight (Figure 13.10)
- Must be installed vertically, unless otherwise allowed by the manufacturer, with cables entering the lower entry face of the enclosure. Cables and conduits may enter the isolator through the side faces if allowed by the manufacturer.

EXAMPLE (CONTINUED)



Connection diagram for the example four-pole switch-disconnector

Step 3

The positive and negative conductors each go through 2 poles. This is a transformerless inverter, so under earth fault conditions, either conductor may switch the full array current and voltage. Therefore, looking at the 2 poles in series configuration in the diagram above, at the 1000 V row, the $I_{(make)}$ and $I_{c\,(break)}$ for the chosen configuration is 52 A. This is higher than 21.25 A, so is acceptable.

The isolator meets all three sizing requirements. Therefore, this isolator and the PV array configuration are compatible.

13.3.4 Summary of DC Disconnection Devices

The following table summarises the requirements for all DC protection devices for strings, sub-arrays and arrays, including overcurrent protection and disconnection. The relevant Australian standards explain how the PV array maximum voltage is calculated.

Location	Protection/ Disconnection Description	Protection/ Disconnection Device	Protection Sizing and Guidelines	Australian Standards
String	String overcurrent protection device (Section 13.2.1)	Fuse or circuit breaker	**Required if:** $I_{SC} \times$ *(No. of strings - 1) ≥ Module reverse current rating* **Sizing:** $1.5 \times I_{SC\_MOD} < I_{TRIP} < 2.4 \times I_{SC\_MOD}$ AND $I_{TRIP} \leq I_{MOD\_REVERSE}$	***AS/NZS 5033:2014*** Clause 3.3.4 and 3.3.5.1
	String disconnection device (Section 13.3.1)	Switch-disconnector, circuit breaker, or plug and socket	• Can be non-load-breaking • Rated for PV array maximum voltage • Current rating ≥ string overcurrent protection or, if no string overcurrent protection present, current rating ≥ CCC of string cable • No live parts may be exposed at any time	***AS/NZS 5033:2014*** Clause 4.3.5.2 and 4.4.1.3
Sub-array	Sub-array overcurrent protection device (Section 13.2.2)	Fuse or circuit breaker	**Required if:** $1.25 \times I_{SC\ ARRAY}$ > CCC of any sub-array cable, switching and connection device OR More than two sub-arrays are present within the array **Sizing:** $1.25 \times I_{SC\ SUB\text{-}ARRAY} \leq I_{TRIP} \leq 2.4 \times I_{SC\ SUB\text{-}ARRAY}$	***AS/NZS 5033:2014*** Clause 3.3.5.2
	Sub-array disconnection device (Section 13.3.2)	Switch-disconnector, circuit breaker, or plug and socket (ELV)	• Can be non-load-breaking • Recommended to be load-breaking for LV systems • Rated for PV array maximum voltage • Current rating ≥ sub-array overcurrent protection or, if no sub-array overcurrent protection present, current rating ≥ CCC of sub-array cable • No live parts may be exposed at any time	***AS/NZS 5033:2014*** Clause 4.2, 4.3.5.2 and 4.4.1.3
Array	Array overcurrent protection device (Section 13.2.3)	Fuse or circuit breaker	**Required if:** Another source of current is available that may cause damage to the PV array when under fault conditions. **Sizing:** $1.25 \times I_{SC\ ARRAY} \leq I_{TRIP} \leq 2.4 \times I_{SC\ ARRAY}$	***AS/NZS 5033:2014*** Clause 3.3.5.3
	Array disconnection device (Section 13.3.3)	Switch-disconnector or circuit breaker	• Load-breaking and lockable in off position • Non-polarised • Voltage rating outlined in Section 13.3.3 • Current rating ≥ array overcurrent protection or, if no array overcurrent protection present, current rating ≥ $1.25 \times I_{SC\text{-}ARRAY}$ • No live parts may be exposed at any time	***AS/NZS 5033:2014*** Clause 4.2, 4.4.1.3, 4.4.1.4 and 4.4.1.5

Chapter 13 Quiz

Question 1

A PV module has an $I_{MOD\ REVERSE}$ of 16 A and an I_{SC} of 5.4 A. For the following array configurations, (i) determine whether string overcurrent protection is required and (ii) If so, determine the size of the string overcurrent protection device.

a. 2 strings of 9 modules.

b. 3 strings of 20 modules.

c. 4 strings of 12 modules.

d. 5 strings of 5 modules.

Question 2

A PV module has an $I_{MOD\ REVERSE}$ of 15A and an I_{SC} of 6.3A. This PV module is used in an array with four strings of eight modules. Determine whether string overcurrent protection is required and if it is, determine the size of the string overcurrent protection device.

Question 3

a. When is sub-array overcurrent protection required?

b. When is array overcurrent protection required?

c. Which calculation do you use to size a sub-array overcurrent protection fuse or circuit breaker?

d. Which calculation do you use to size an array overcurrent protection fuse or circuit breaker?

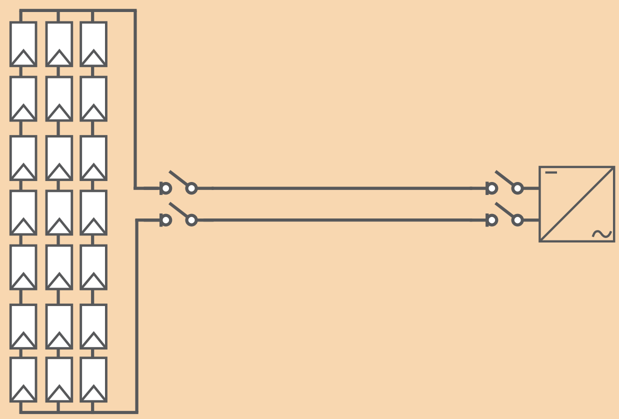
Question 4

Can functional earthing be used with transformerless inverters?

Question 5

Determine the maximum array voltage and current that would be used to check the suitability of the PV array DC isolator, given that:

- V_{OC} = 44.3 V
- I_{SC} = 8.1 A
- V_{MP} = 37.1 V
- I_{MP} = 6.8 A
- γ_{VOC} = –0.30%/°C
- γ_{VMP} = –0.5%/°C
- Minimum site temperature = 2°C
- Maximum site temperature = 41°C



The size of the voltage rise in a cable can be calculated using the resistance of the cable and the amount of current flowing through the cable. As the resistance of a cable is proportionate to the conductor's CSA and the length of the cable, the voltage rise is a function of three parameters:

1. Conductor CSA;
2. Length of the conductor; and
3. Current flow through the conductor.

Voltage rise increases with higher resistance, so smaller cables (smaller CSA), longer cable runs and higher current flow in the cable increase the voltage rise. Therefore, voltage rise can be reduced by suitable cable design, including reducing the length of the cable or increasing the cable CSA.

The relationship between voltage drop, cable cross-sectional area (CSA), cable length and current flow is:

$$V_d = \frac{2 \times L \times I \times \rho \times \cos\Phi}{A_{CABLE}}$$

Where:

- V_d = Voltage drop (in V)
- L = Route length of cable (in m) Multiplying by two adjusts for total circuit cable length.
- I = Current flow (in A)[†]. For DC calculations, the I_{MP} current (at STC) should be used and not the I_{SC} current.
- ρ = Resistivity of the conductor (in Ω/m/mm²)
- $\cos\Phi$ = Power factor (include only for AC cables)
- A_{CABLE} = CSA of cable (in mm²)

AUSTRALIAN STANDARDS

For LV systems, as per ***AS/NZS 5033:2014*** Clause 4.3.6.2, tinned copper cabling is recommended for use to reduce the cable's degradation over time.

However, resistivity depends on the material of the conductor (e.g. copper, tinned copper, aluminium) as well as temperature. For this reason, it is industry standard in Australia to state the equation in terms of V_C, voltage drop specified in millivolts per amp-metre (mV/Am), and refer to voltage drop tables specific to cable type, installation method, conductor CSA and temperature.

$$V_d = \frac{L \times I \times V_C}{1{,}000}$$

Where:

- V_d = Actual voltage drop (in V)
- L = Route length (in m)
- I = Current flow (in A)
- V_C = Millivolt drop per amp-metre route length (in mV/Am)

AUSTRALIAN STANDARDS

AS/NZS 3008.1.1:2017 Clause 4.2 specifies how to determine the voltage drop using V_C. Tables 40 to 51 in ***AS/NZS 3008.1.1:2017*** provide three-phase V_C values for different conductor types, sizes and temperatures.

Tables of V_C values may be provided by the cable manufacturer, or otherwise can be found in the relevant Australian standards. The voltage drop values are typically for three-phase AC circuits, which can then be converted to single phase AC or DC values by multiplying by 1.155.

EXAMPLE

The cable route between a battery inverter and main switchboard is 4 metres. The inverter has a maximum current output of 13 A, single phase AC. The cable manufacturer provides the following three-phase VC values at 60°C for various conductor CSAs:

2.5 mm^2 copper multicore cable: 14.9 mV/Am

4 mm^2 copper multicore cable: 9.24 mV/Am

6 mm^2 copper multicore cable: 6.18 mV/Am

Since these values are for a three-phase circuit, they will need to be multiplied by 1.155 to find the single-phase voltage drop.

If using 2.5 mm^2 cable, the actual voltage drop will be:

$$V_d = \frac{4\text{ m} \times 13\text{ A} \times (14.9\text{ mV/Am} \times 1.155)}{1{,}000}$$

$$= 0.89\text{ V}$$

However, if a larger 6 mm^2 cable were to be used, the voltage drop would be:

$$V_d = \frac{4\text{ m} \times 13\text{ A} \times (6.18\text{ mV/Am} \times 1.155)}{1{,}000}$$

$$= 0.37\text{ V}$$

NOTE

In some cases, V_C tables are only available for three-phase values. Multiply the three-phase values by 1.155 to convert to single-phase values Similarly, divide the maximum V_C in single phase AC or DC values by 1.155 to convert to three-phase values.

To find the voltage drop as a loss percentage, simply divide the voltage drop in volts by the system voltage:

$$Loss = \frac{V_d}{V_{DC}}$$

Where:

- ***Loss*** = Voltage drop in the cable (dimensionless, i.e. 5% = 0.05)
- V_d = Voltage drop (in V)
- V_{DC} = System voltage (in V)

Alternatively, the previous formulae can be rearranged to give the maximum permitted V_C for a given voltage drop:

$$V_C = \frac{1{,}000 \times Loss \times V_{DC}}{L \times I}$$

Where:

- V_C = Millivolt drop per amp-metre route length (in mV/Am)
- ***Loss*** = Maximum permissible voltage drop in the cable (dimensionless, i.e. 5% = 0.05)
- V_{DC} = System voltage (in V)
- L = Route length (in m)
- I = Current flow through the cable (in A)

In conjunction with tabulated V_C values for a variety of cable sizes, the minimum required conductor CSA to meet the voltage drop requirements can then be determined.

Table 14.1 shows tabulated three-phase V_C values for a particular cable. Similar tables can be obtained from local standards or cable manufacturers.

***Table 14.1:** Three-phase V_C for single-core flexible cable in touching formation (mV/Am).*

Conductor CSA (mm²)	Conductor temperature (°C)				
	45	60	75	90	110
0.5	74.2	78.2	82.2	86.1	91.4
1.0	37.1	39.1	41.1	43.1	45.7
1.5	25.3	26.7	28.0	29.4	31.2
2.5	15.2	16.0	16.8	17.6	18.7
4	9.42	9.92	10.4	10.9	11.6
6	6.28	6.62	6.96	7.29	7.74
10	3.64	3.84	4.03	4.22	4.48
16	2.31	2.43	2.56	2.68	2.85
25	1.50	1.58	1.66	1.74	1.84
35	1.07	1.13	1.18	1.24	1.31
50	0.760	0.798	0.837	0.875	0.926
70	0.551	0.577	0.603	0.630	0.665

EXAMPLE

Using Table 14.1, determine the minimum cable size required for an array where:
Route length = 20 m,
Maximum current = 15 A,
System voltage = 24 V, and
Maximum allowable voltage drop = 5%.

$$Maximum\ V_C = \frac{1{,}000 \times 0.05 \times 24\ V}{20\ m \times 15\ A} = 4\ \mathrm{mV/Am\ (DC)}$$

Converting to three-phase:

$$4\ mV/Am \div 1.155 = 3.46\ mV/Am\ (three\text{-}phase\ AC)$$

Assuming the selected cable may operate up to its rated insulation temperature of 90°C, the minimum conductor CSA that meets the calculated V_C requirement is a 16 mm² cable.

DID YOU KNOW

Most commercial PV modules are manufactured with 4 mm² cables preattached.

The actual CSA of the cable selected will depend on the available cable sizes. For example, typical CSAs for PV module string cables are 1.5 mm², 2.5 mm², 4 mm² and 6 mm². Selecting a cable larger than required will increase the cabling cost but will result in reduced power losses. The relative advantages of increased cable size would have to be weighed up.

If the maximum permissible voltage drop is to be calculated across various types of cable, the permissible voltage drop can be divided evenly across these cables.

EXAMPLE

A PV system has two string cables and one array cable to be sized for the DC side of the system. The maximum permissible voltage drop between the furthest module and the inverter is 3%.

The array cable will need to carry more current than the string cables and so it should be sized separately. This means that the 3% voltage drop can be split evenly between the string cables and the array cable.

Dividing 3% voltage drop by two = 1.5%

Therefore, the string cables should be sized using a total permissible voltage drop of 1.5% and the array cable should be sized using a permissible voltage drop of 1.5%.

14.1.3 Cable Routes and Length

The cable routes in a grid-connected PV system are initially dependent on the locations of the system components. However, the locations of the system components may be chosen so that the resulting cable routes meet the performance or cost requirements of a specific cable size.

As shown in Section 14.1.2, the voltage drop in a cable is proportional to the length of the cable. Therefore, using cable routes that minimise the cable lengths will mean that smaller cables can be used without excessive voltage drops. The voltage drop is also proportional to the amount of current that is being carried by the cable. This means that cables with higher currents should be kept as short as possible. The requirement to meet the correct cable sizing and the system's cabling costs should be applied when locating the system equipment and determining cable lengths and routes.

AUSTRALIAN STANDARDS

AS/NZS 5033:2014 Clause 3.5.2 states that conductive loops in array wiring should be minimised.

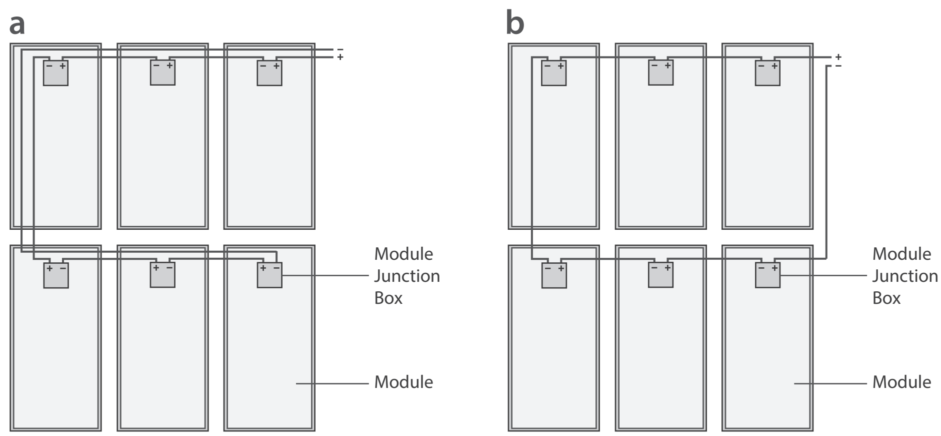


***Figure 14.2**: a) PV string cable with minimised inductive loop area. b) PV string cable that has an inductive loop. This should be avoided.*

Wiring Loops

The array wiring should be designed to minimise inductive loops (Figure 14.2). Reducing inductive loops will lower the risk of lightning strikes at the array, as well as reducing interference to AM and FM radio signals.

14.2 DC Cable Design

DC cables are installed for the DC side of the grid-connected PV system. Depending on the array configuration, they include string cables, sub-array cables and array cables.

The requirements of DC cables include:

- A CCC rating suitable for the function of the cable and the protection installed on the cable (calculations shown for each cable type).
- A minimum CSA so that the maximum permissible voltage drop is not exceeded (calculations shown for each cable type).
- A voltage rating equal to at least the PV array maximum voltage.
- A temperature and durability rating for the cable compatible with the environment where the cable will be installed. For example, if the cabling is to be exposed to sunlight, the cable should be UV-resistant or housed in UV-resistant conduit.
- Double insulated.
- Contained within conduit as required.

AUSTRALIAN STANDARDS

Refer to ***AS/NZS 5033:2014*** Clause 4.3.6.1 and Table 4.2 to calculate the minimum required CCC for each DC cable in a PV system, then refer to either the cable manufacturer's specifications or the relevant tables for flexible cables in ***AS/NZS 3008.1.1:2017*** for appropriate size and de-rating factors due to method of installation.

AUSTRALIAN STANDARDS

AS/NZS 3000:2018 Clause 3.4 provides guidance on sizing cables according to CCC.

IMPORTANT

The maximum voltage rating of any cable must **never** be exceeded.

Some solar arrays can operate at ±1,000V DC. This voltage level may exceed the allowable voltage for some cables.

It is recommended that multi-stranded DC cables be used, as shown in Figure 14.3.

Figure 14.3: *A solar DC cable with maximum voltage rated at 1,000 V.*

14.2.1 String Cables

The PV array's string cables connect the PV modules in series. The majority of PV modules used in grid-connected PV systems are fitted with a pair of string cables pre-wired with a plug and socket to interconnect the modules in a string (Figure 14.4). String cables are often terminated in the array combiner box, which connects the array cable to the inverter.

Figure 14.4*: A PV module pre-wired with plug-and-socket connectors.*

REMEMBER

String overcurrent protection limits the maximum current able to pass through the string cables.

The manufacturers of string cables will specify the CCC rating and maximum voltage rating of their cables. These specifications must be respected at all times and are usually available for cables of a nominal conductor area of 2.5 mm^2 to 6 mm^2.

String Cables: Calculating the Required CCC

Each string cable should be capable of carrying all possible current sources in the system. As overcurrent protection limits the amount of current able to safely pass through different parts of the system, the CCC rating of a string cable should take any overcurrent protection in the system into account.

The string cables may also carry current being fed from a number of strings to a single string if that single string is not operating at the same voltage level as the other strings.

If string overcurrent protection will be installed:

The string cable should be able to carry any current able to pass through the string overcurrent protection.

$$CCC \geq \textit{Rating of string overcurrent protection}$$

If string overcurrent protection will not be installed:

The string cable should be able to carry the combined short-circuit currents from the other strings (with safety margin) as well as any current able to pass through downstream overcurrent protection.

$$CCC \geq I_n + (1.25 \times I_{SC\ MOD}) \times (Number\ of\ strings - 1)$$

Where:

- ***CCC*** = Current carrying capacity rating of the cable (in A);
- ***I_n*** = Downstream overcurrent protection (in A)
- ***I_{SC}*** = Short circuit current of the module (in A); and
- ***Number of strings*** = Total number of parallel connected strings protected by the nearest overcurrent device.

If there is no downstream overcurrent protection, I_n is replaced by the inverter ***back-feed current*** and the number of strings is equal to the number of strings in the whole array.

If there is only one string in the whole array, the string cable should be rated to carry the short circuit current of the string, with a safety margin: $1.25 \times I_{SC\ MOD}$.

DEFINITION

The inverter back-feed current is the amount of current that the inverter could feed into the DC array cable during a fault condition.

EXAMPLE 1

A PV system is made up of five strings with the following characteristics:

$I_{SC\ MOD} = 5.1$ A.

Module reverse current rating = 20 A.

Using the string overcurrent protection formula described in Chapter 13:

$I_{SC\ MOD} \times$ (Number of strings – 1)

$= 5.1 \times (5 - 1)$

$= 20.4$ A

As this is greater than the module reverse current rating, string overcurrent protection is required.

The formula for calculating the size of the string overcurrent protection is also given in Chapter 13:

$1.5 \times I_{SC\ MOD} \leq I_{TRIP} \leq 2.4 \times I_{SC\ MOD}$

$1.5 \times 5.1 \leq I_{TRIP} \leq 2.4 \times 5.1$

$7.65\ A \leq I_{TRIP} \leq 12.24\ A$

Therefore a 10 A overcurrent device could be used.

As string overcurrent protection is present, the minimum CCC rating of the string cable is equal to the rating of the overcurrent protection, so it is equal to 10 A.

Example 2

A PV system is made up of two strings with the following characteristics:

$I_{SC\ MOD} = 5.1$ A.

Module reverse current rating = 20 A.

Using the string overcurrent protection formula as described in Chapter 13:

$I_{SC\ MOD} \times$ (number of strings – 1)

$= 5.1 \times (2 - 1)$

$= 5.1$ A

As this figure is less than the module's reverse current rating, string overcurrent protection is not required. There is no external current source and so array overcurrent is also not required.

The string cable needs to be able to carry the short circuit currents from the other strings and the inverter back-feed current. In this installation, the inverter back-feed current is equal to 1 A.

$$CCC \geq I_n + (1.25 \times I_{SC\ MOD}) \times (Number\ of\ strings - 1)$$

$$CCC \geq 1 + 1.25 \times 5.1 \times (2 - 1)$$

$$CCC \geq 7.375\ A$$

Therefore, the minimum CCC rating of the string is 7.375 A.

NOTE

If the interconnection cables supplied with the modules are not sized correctly for the required CSA calculated for string cables, additional voltage drop calculations might need to be performed and, as required, larger string cables may need to be installed.

String Cables: Calculating the Minimum CSA

To keep the voltage drop below the maximum threshold, the minimum CSA of the string cables should be calculated. It is calculated using the method outlined in Section 14.1.2:

As discussed in Section 14.1.2, the modules in a string should be connected such that the area of inductive loops is minimised. This means that the positive string cable and the negative string cable may be different lengths.

According to the standards, the maximum permissible DC voltage drop is 3%: this number is a combined limit across all cabling on the DC side, including the string cabling and the array cabling. Therefore, it is reasonable to allocate different amounts of the maximum permissible voltage drop to different parts of the DC side. For example, if the string cabling has a 1% voltage drop then the remainder of the DC cabling can have a maximum of 2% voltage drop to keep below the combined permissible maximum of 3%.

AUSTRALIAN STANDARDS

AS/NZS 5033:2014 Clause 2.1.10 and the ***CEC guidelines*** state the maximum DC voltage drop should not exceed 3% under maximum current conditions. For more information, please refer to Section 15.1.6.

EXAMPLE:

The MPP voltage of a string at STC is 216 V and the string current is 5 A. The length of the positive cable is 18 m and the length of the negative cable is 18 m from the furthest module to the inverter.

As per the applicable standards, the maximum permissible voltage drop between the furthest module and the inverter is 3%. This figure also needs to include the array cable voltage drop, so the string cable should have a maximum permissible voltage drop of 1.5%.

Typical CSAs for PV module cables are 1.5 mm², 2.5 mm², 4 mm² and 6 mm². For this system, 1.5 mm² is satisfactory. A larger cable could also be selected, resulting in reduced power loss (but increased cost).

Using Table 14.1, determine the minimum cable size required for the string cables.

$$Maximum\ V_C = \frac{1{,}000 \times Loss \times V_{DC}}{L \times I}$$

$$= \frac{1{,}000 \times 0.015 \times 216\ \text{V}}{18\ \text{m} \times 5\ \text{A}}$$

$$= 36\ \text{mV/Am}\ (DC)$$

Converting to three-phase:

$$\frac{36\ \text{mV/Am}}{1.155} = 31.17\ \text{mV/Am}\ (three\text{-}phase\ AC)$$

Assuming the selected cable may operate up to its rated insulation temperature of 90°C, the minimum conductor CSA that meets the calculated VC requirement is a 1.5mm² cable.

14.2.2 Sub-array Cables

An array may be broken up into sub-arrays, comprising a number of parallel strings. The sub-arrays are connected in parallel to form the full array. The use of sub-arrays will reduce the potential fault current in some parts of the system.

The sub-array cables connect the string combiner box (the connection point of the parallel strings) and the array combiner box. To size the sub-array cable, use the same principles as those for sizing the string cables:

Sub-array Cables: Calculating the Required CCC

Sizing sub-array cables uses similar principles as those used for sizing string cables. Each sub-array cable should be capable of carrying the system's total current sources, taking into account any system overcurrent protection.

The sub-array cable should be able to carry its short-circuit current, and it may also need to account for when the sub-array is fed currents from the other sub-arrays because the sub-array is not operating at the same level as the other sub-arrays.

If sub-array overcurrent protection will be installed:

The sub-array cable should carry any current that can pass through the sub-array overcurrent protection.

$$CCC \geq \textit{Rating of sub-array overcurrent protection}$$

If sub-array overcurrent protection will not be installed:

The sub-array cable should carry the greater of:

1. Its own short-circuit current (with safety margin):

$$CCC \geq 1.25 \times \textit{sub-array short circuit current}$$

OR

2. The combined short-circuit currents from the other sub-arrays (with safety margin), as well as any current that can pass through downstream overcurrent protection:

$$CCC \geq I_n + (1.25 \times \textit{Sum of } I_{SC} \textit{ from other sub-arrays})$$

Where

- I_n = downstream overcurrent protection.

If there is no downstream overcurrent protection, In is replaced by the inverter back-feed current.

REMEMBER

Sub-array overcurrent protection limits the maximum current that can pass through the sub-array cables.

Sub-array Cables: Calculating the Minimum CSA

To keep the voltage drop below the maximum threshold, the minimum CSA of the sub-array cables should be calculated. It is calculated using the method outlined in Section 14.1.2:

According to the standards, the maximum permissible DC voltage drop is 3%. This includes the string cable voltage drop, the sub-array voltage drop and the array cable voltage drop. For systems that have sub-arrays, it is reasonable to divide the voltage drop threshold by three for each type of cable: array, sub-array and string. This means the permissible voltage drop is 1% for each of these cables.

EXAMPLE

An array has two sub-arrays, each one comprised of four strings.

The V_{MPP} at STC of each string is 216 V and the current in the string is 5 A. The V_{MPP} of the sub-array cable remains at 216 V, but the current is multiplied by 4 (four parallel strings) to give 20 A.

The sub-array cables will be 5 m long and the permissible voltage drop is set at 1%, as per the principles outlined in this section.

Using Table 14.1, determine the minimum cable size required for the sub-array cables.

$$\begin{aligned} Maximum\ V_C &= \frac{1{,}000 \times Loss \times V_{DC}}{L \times I} \\ &= \frac{1{,}000 \times 0.01 \times 216\text{ V}}{5\text{ m} \times 20\text{ A}} \\ &= 21.6\text{ mV/Am } (DC) \end{aligned}$$

Converting to three-phase:

$$\frac{21.6\text{ mV/Am}}{1.155} = 18.7\text{ mV/Am } (three\text{-}phase\ AC)$$

Assuming the selected cable may operate up to its rated insulation temperature of 90°C, the minimum conductor CSA that meets the calculated V_C requirement is a $2.5mm^2$ cable.

14.2.3 Array Cables

The array cables connect the PV array to the PV disconnector and then to the DC input of the inverter.

Array Cables: Calculating the Required CCC

The array cable should be capable of carrying all currents from the PV array as well as any possible back-feed current from the inverter. The array cable for a standard grid-connected PV system will not carry any current from external sources, such as a battery bank. Therefore, it is expected that there will be no array overcurrent protection installed.

The array cable should be sized to carry whichever is the greater of:

1. The array short circuit current (with safety margin):

$$CCC \geq 1.25 \times array\ short\ circuit\ current$$

OR

2. The inverter back-feed current:

$$CCC \geq inverter\ backfeed\ current$$

Array Cables: Calculating the Minimum CSA

To keep the voltage drop below the maximum threshold, the minimum CSA of the array cables should be calculated. This figure is calculated using the method outlined in Section 14.1.2:

The maximum permissible voltage drop per cable will vary according to the array configuration. For systems that have sub-arrays, it is reasonable to divide the voltage drop threshold by three for each type of cable: array, sub-array and string. This means the permissible voltage drop is 1% for each of these cables. For systems without sub-arrays, the maximum permissible voltage drop would be divided between the two cable types: array and string. The permissible voltage drop would be 1.5% for each of these cables.

> ***EXAMPLE***
>
> An array comprises four strings. The V_{MPP} at STC of each string is 216 V and the string current is 5 A. The V_{MPP} of the array cable remains at 216 V; the array current is 20 A: 4 parallel strings at 5 A.
>
> The array cables will be 10m long and the permissible voltage drop is set at 1.5% as per the principles outlined in this section.
>
> Using Table 14.1, determine the minimum cable size required for the array cables.
>
> $$Maximum\ V_C = \frac{1{,}000 \times Loss \times V_{DC}}{L \times I}$$
>
> $$= \frac{1{,}000 \times 0.015 \times 216\ \text{V}}{10\ \text{m} \times 20\ \text{A}}$$
>
> $$= 16.2\ \text{mV/Am}\ (DC)$$
>
> Converting to three-phase:
>
> $$\frac{16.2\ \text{mV/Am}}{1.155} = 14.03\ \text{mV/Am}\ (three\text{-}phase\ AC)$$
>
> Assuming the selected cable may operate up to its rated insulation temperature of 90°C, the minimum conductor CSA that meets the calculated V_C requirement is a 4mm² cable.

> **RESOURCE**
>
> The GSES publication 'Grid-connected PV Systems with Battery Storage' provides the additional information needed to design a system that has a battery bank.

14.3 AC Cable Design

The AC cables on a grid-connected PV system are used between the inverter and the grid connection point. The AC cable design for a grid-connected PV system will relate to the cables between the inverter and the switchboard (or the distribution board if applicable). However, potential voltage rise at the inverter could require a reassessment of the suitability of the wiring between the switchboard (or distribution board) and the grid connection point.

AUSTRALIAN STANDARDS

AS/NZS 3008.1.1:2017 states the DC and AC de-rated CCC for different cables.

AS/NZS 4777.1:2016 outlines the AC cable requirements in a grid-connected PV system.

14.3.1 AC Inverter Cable

The AC inverter cable connects the inverter to the main electrical supply. This is usually at the switchboard, but some installations might connect the inverter to the nearest distribution board. For example, an array installed on a shed roof could be connected to the grid via the shed distribution board. As outlined in Section 11.6, the nearest distribution board may be used only if the PV system has a net metering arrangement.

The voltage rating of the AC inverter cable will be the same as that for standard building cables, around 230 V_{RMS}. The required CCC and minimum CSA calculations are set out in this section. The cable must also comply with the following requirements:

- A temperature and durability rating relative to the environment in which the cable will be installed. For example, if the cabling is exposed, it should be UV-resistant material or housed in UV-resistant conduit.
- Insulated or enclosed as required.

REMEMBER

According to the CEC guidelines, the maximum voltage drop between the inverter and the switchboard should be 1%.

AC Inverter Cable: Calculating the Required CCC

The AC inverter cable connects the inverter and the switchboard (or distribution board). Therefore, the CCC of the AC cables must be greater than the maximum AC output current from the inverter.

The AC cable should also be able to carry any fault current from the grid, such as a fault on the AC cable between the inverter and the switchboard. This fault current is limited by the circuit breaker at the switchboard and so the CCC of the AC cable should be greater than or equal to the rating of this circuit breaker.

AC Inverter Cable: Calculating the Minimum CSA

To keep the voltage rise below the maximum permitted, the minimum CSA should be calculated for the AC inverter cable. As mentioned in Section 14.1.2, the AC inverter cable is usually as short as possible, which will reduce the size of the CSA required.

The minimum CSA of a single phase AC cable is calculated by adjusting the formula given in Section 14.1.2:

$$V_C = \frac{1{,}000 \times Loss \times V_{AC}}{L \times I}$$

Where:

- V_C = Millivolt drop per amp-metre route length (in mV/Am)
- ***Loss*** = Maximum voltage drop in the cable (dimensionless, i.e. 5% = 0.05)
- V_{AC} = AC voltage of the grid (in V)
- L = Route length (in m)
- I = Current flow through the cable (in A)

Many AC cable manufacturers provide tables specifying the voltage drop/rise per metre of AC cable for various currents.

> ***AUSTRALIAN STANDARDS***
> ***AS/NZS 4509.2:2010*** includes tables outlining the voltage drop per ampere per metre of AC cables for various cable sizes.

EXAMPLE:
The inverter for use with a 2 kWp PV array is to be installed so that the AC cabling route will be 30 m between the inverter and the main switchboard.
What is the minimum CSA required for the AC cabling to ensure that the voltage rise will be less than 1%?
Assume the following:
Maximum inverter output current = 11 A
Single phase supply: AC voltage = 230 V_{RMS}

Using Table 14.1,

$$Maximum\ V_C = \frac{1{,}000 \times Loss \times V_{AC}}{L \times I} = \frac{1{,}000 \times 0.01 \times 230\ \mathrm{V}}{30\ \mathrm{m} \times 11\ \mathrm{A}} = 6.97\ \mathrm{mV/Am}\ (\textit{single-phase AC})$$

Converting to three-phase:

$$\frac{6.97\ \mathrm{mV/Am}}{1.155} = 6.03\ \mathrm{mV/Am}\ (\textit{three-phase AC})$$

Assuming the selected cable may operate up to its rated insulation temperature of 90°C, the minimum conductor CSA that meets the calculated V_C requirement is a $10mm^2$ cable.

14.3.2 Voltage Rise at the Inverter

The AC connection between the inverter and the electricity grid is made up of multiple cable runs: the inverter to the switchboard, the switchboard to the point of attachment, and the point of attachment to the grid. The voltage rise along this cable run, between the inverter and the grid, results in a voltage rise at the AC output of the inverter (Figure 14.5).

> ***AUSTRALIAN STANDARDS***
>
> According to ***AS/NZS 4777.1:2016***, the overall voltage rise from the point of supply to the inverter a.c. terminals (grid-interactive port) shall not exceed 2% of the nominal voltage at the point of supply.

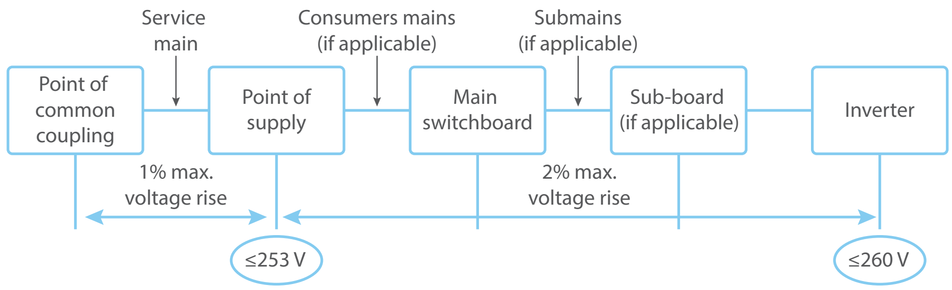


Figure 14.5: Voltage rise between the inverter and point of attachment to the grid.

If the voltage rise at the AC output of an inverter is excessive, this can cause the inverter to trip (i.e. disconnect): this happens when the inverter finds that the grid voltage is outside of the required parameters. (Figure 14.6).

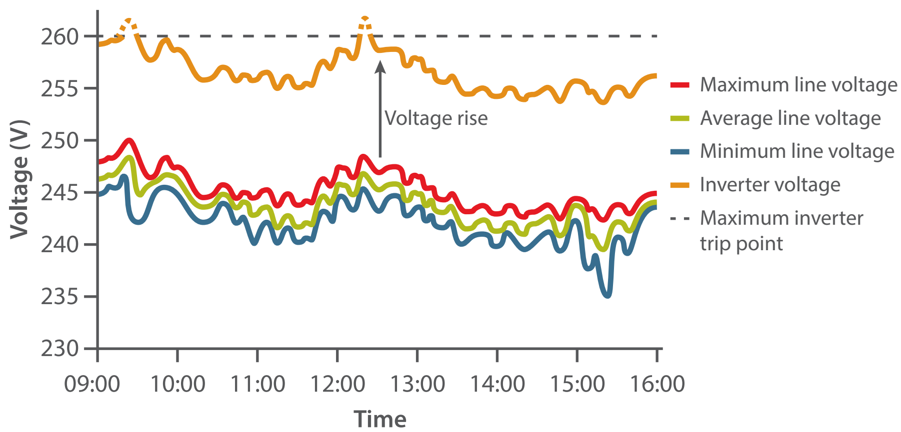


Figure 14.6: Example of recorded inverter voltage readings compared with the grid; the voltage rise between the grid and inverter is shown causing the inverter to exceed its maximum trip point twice, thus causing a false trip.

Grid voltage tolerance tripping is more likely to occur in areas where the grid voltage regularly sits at its upper voltage limit. In these areas, there does not need to be a large voltage rise at the inverter to cause the grid voltage to exceed its voltage limits and trip. Voltage rise is also generally more of a problem in large systems, in which significant cable losses can result in a high voltage rise.

If tripping caused by voltage rise will be an issue for a grid-connected PV system, there are three main options that can be explored:

1. ***Reduce the voltage rise:*** By reducing the resistance in the cable run between the inverter and the point of attachment to the grid, the voltage rise at the inverter may be reduced. This could be achieved by increasing the conductor CSA or by reducing the length of the cable run (i.e. locating the inverter closer to the

point of attachment to the grid), or it could mean replacing the main supply cables between the switchboard and the grid connection point. The resistance presented by the grid in this scenario is also responsible for voltage rise, but this issue cannot be rectified by the system designer and could require discussions with the local network provider.

2. ***Increase the inverter voltage limits:*** Some inverters may allow the voltage limit to be increased so that the inverter will not trip due to voltage rise. It is possible that the inverter's higher voltage set points for a 230V AC grid be adjusted from 260 V to 265 V AC. Inverter adjustments as outlined would need authorisation from the inverter manufacturer and network provider.
3. ***Use an inverter designed to 'ride through' grid fluctuations:*** Some inverters may have the ability to ride through brief fluctuations in the grid voltage; this can even promote better stability in the grid. This type of inverter could be beneficial for a PV system connected to a grid that has regular voltage excursions.

NOTE

If voltage rise is identified as being due to the system being located near a transformer where the voltage settings are at their upper limit, solutions 1 and 2 might be the only options.

Chapter 14 Quiz

Question 1

a. According to ***AS/NZS 5033:2014***, what is the maximum allowable DC voltage drop in a solar PV system?

b. According to ***AS/NZS 5033:2014***, what is the maximum allowable AC voltage drop in a solar PV system?

Question 2

Why should the CCC of all cables be known?

Question 3

An array has four strings of nine modules and the following specifications:

- Module I_{MP} = 5.2 A
- Module V_{MPP} = 35.1 V
- String cable length = 14 m
- Array cable length = 22 m

Assume the cable has the same specifications as in ***AS/NZS 3008.1.1:2017*** Table 47 and a maximum conductor temperature of 90°C.

The cables should be sized to have a maximum 1.5% voltage drop on the string cables and a 1.5% voltage drop on the array cables.

a. Calculate the minimum string cable CSA.

b. Calculate the minimum array cable CSA.

Question 4

You are supplied with a reel of 4 mm^2 cable to use as the array cable for a solar PV installation. The array has five strings of ten modules and the following specifications:

- Module I_{MP} = 7.9 A
- Module V_{MPP} = 36.1 V
- String cable length = 20 m
- Array cable length = 11 m

Assume the cable has the same specifications as in ***AS/NZS 3008.1.1:2017*** Table 47 and a maximum conductor temperature of 60°C.

a. Calculate the % voltage drop on the array cable.

b. Calculate the maximum allowable % voltage drop on the string cables.

c. Calculate the minimum string cable CSA.

Question 5

The distance between an inverter and the main switchboard is 26 m. What is the minimum cable CSA that will ensure the voltage drop will be less than 1%?

Assume the following:

- I_{AC} = 12 A
- V = Single-phase 230 V_{RMS}

Assume the cable has the same specifications as in ***AS/NZS 3008.1.1:2017*** Table 47 and a maximum conductor temperature of 90°C.

Question 6

Why should cables be as short as possible? How can system design and installation minimise the length of system cables?

14.2.2 Sub-array Cables

An array may be broken up into sub-arrays, comprising a number of parallel strings. The sub-arrays are connected in parallel to form the full array. The use of sub-arrays will reduce the potential fault current in some parts of the system.

The sub-array cables connect the string combiner box (the connection point of the parallel strings) and the array combiner box. To size the sub-array cable, use the same principles as those for sizing the string cables:

Sub-array Cables: Calculating the Required CCC

Sizing sub-array cables uses similar principles as those used for sizing string cables. Each sub-array cable should be capable of carrying the system's total current sources, taking into account any system overcurrent protection.

The sub-array cable should be able to carry its short-circuit current, and it may also need to account for when the sub-array is fed currents from the other sub-arrays because the sub-array is not operating at the same level as the other sub-arrays.

If sub-array overcurrent protection will be installed:

The sub-array cable should carry any current that can pass through the sub-array overcurrent protection.

$$CCC \geq \textit{Rating of sub-array overcurrent protection}$$

If sub-array overcurrent protection will not be installed:

The sub-array cable should carry the greater of:

1. Its own short-circuit current (with safety margin):

$$CCC \geq 1.25 \times \textit{sub-array short circuit current}$$

OR

2. The combined short-circuit currents from the other sub-arrays (with safety margin), as well as any current that can pass through downstream overcurrent protection:

$$CCC \geq I_n + (1.25 \times \textit{Sum of } I_{SC} \textit{ from other sub-arrays})$$

Where

- I_n = downstream overcurrent protection.

If there is no downstream overcurrent protection, In is replaced by the inverter back-feed current.

REMEMBER

Sub-array overcurrent protection limits the maximum current that can pass through the sub-array cables.

Sub-array Cables: Calculating the Minimum CSA

To keep the voltage drop below the maximum threshold, the minimum CSA of the sub-array cables should be calculated. It is calculated using the method outlined in Section 14.1.2:

According to the standards, the maximum permissible DC voltage drop is 3%. This includes the string cable voltage drop, the sub-array voltage drop and the array cable voltage drop. For systems that have sub-arrays, it is reasonable to divide the voltage drop threshold by three for each type of cable: array, sub-array and string. This means the permissible voltage drop is 1% for each of these cables.

EXAMPLE

An array has two sub-arrays, each one comprised of four strings.
The V_{MPP} at STC of each string is 216 V and the current in the string is 5 A. The V_{MPP} of the sub-array cable remains at 216 V, but the current is multiplied by 4 (four parallel strings) to give 20 A.
The sub-array cables will be 5 m long and the permissible voltage drop is set at 1%, as per the principles outlined in this section.
Using Table 14.1, determine the minimum cable size required for the sub-array cables.

$$\begin{aligned} \textit{Maximum } V_C &= \frac{1{,}000 \times \textit{Loss} \times V_{DC}}{L \times I} \\ &= \frac{1{,}000 \times 0.01 \times 216\ \text{V}}{5\ \text{m} \times 20\ \text{A}} \\ &= 21.6\ \text{mV/Am}\ (DC) \end{aligned}$$

Converting to three-phase:

$$\frac{21.6\ \text{mV/Am}}{1.155} = 18.7\ \text{mV/Am}\ (\textit{three-phase AC})$$

Assuming the selected cable may operate up to its rated insulation temperature of 90°C, the minimum conductor CSA that meets the calculated V_C requirement is a 2.5mm² cable.

14.2.3 Array Cables

The array cables connect the PV array to the PV disconnector and then to the DC input of the inverter.

Array Cables: Calculating the Required CCC

The array cable should be capable of carrying all currents from the PV array as well as any possible back-feed current from the inverter. The array cable for a standard grid-connected PV system will not carry any current from external sources, such as a battery bank. Therefore, it is expected that there will be no array overcurrent protection installed.

RESOURCE
The GSES publication 'Grid-connected PV Systems with Battery Storage' provides the additional information needed to design a system that has a battery bank.

The array cable should be sized to carry whichever is the greater of:

1. The array short circuit current (with safety margin):

$$CCC \geq 1.25 \times array\ short\ circuit\ current$$

OR

2. The inverter back-feed current:

$$CCC \geq inverter\ backfeed\ current$$

Array Cables: Calculating the Minimum CSA

To keep the voltage drop below the maximum threshold, the minimum CSA of the array cables should be calculated. This figure is calculated using the method outlined in Section 14.1.2:

The maximum permissible voltage drop per cable will vary according to the array configuration. For systems that have sub-arrays, it is reasonable to divide the voltage drop threshold by three for each type of cable: array, sub-array and string. This means the permissible voltage drop is 1% for each of these cables. For systems without sub-arrays, the maximum permissible voltage drop would be divided between the two cable types: array and string. The permissible voltage drop would be 1.5% for each of these cables.

EXAMPLE

An array comprises four strings. The V_{MPP} at STC of each string is 216 V and the string current is 5 A. The V_{MPP} of the array cable remains at 216 V; the array current is 20 A: 4 parallel strings at 5 A.

The array cables will be 10m long and the permissible voltage drop is set at 1.5% as per the principles outlined in this section.

Using Table 14.1, determine the minimum cable size required for the array cables.

$$Maximum\ V_C = \frac{1{,}000 \times Loss \times V_{DC}}{L \times I}$$

$$= \frac{1{,}000 \times 0.015 \times 216\ \text{V}}{10\ \text{m} \times 20\ \text{A}}$$

$$= 16.2\ \text{mV/Am}\ (DC)$$

Converting to three-phase:

$$\frac{16.2\ \text{mV/Am}}{1.155} = 14.03\ \text{mV/Am}\ (three\text{-}phase\ AC)$$

Assuming the selected cable may operate up to its rated insulation temperature of 90°C, the minimum conductor CSA that meets the calculated V_C requirement is a $4mm^2$ cable.

14.3 AC Cable Design

The AC cables on a grid-connected PV system are used between the inverter and the grid connection point. The AC cable design for a grid-connected PV system will relate to the cables between the inverter and the switchboard (or the distribution board if applicable). However, potential voltage rise at the inverter could require a reassessment of the suitability of the wiring between the switchboard (or distribution board) and the grid connection point.

AUSTRALIAN STANDARDS

AS/NZS 3008.1.1:2017 states the DC and AC de-rated CCC for different cables.

AS/NZS 4777.1:2016 outlines the AC cable requirements in a grid-connected PV system.

14.3.1 AC Inverter Cable

The AC inverter cable connects the inverter to the main electrical supply. This is usually at the switchboard, but some installations might connect the inverter to the nearest distribution board. For example, an array installed on a shed roof could be connected to the grid via the shed distribution board. As outlined in Section 11.6, the nearest distribution board may be used only if the PV system has a net metering arrangement.

The voltage rating of the AC inverter cable will be the same as that for standard building cables, around 230 V_{RMS}. The required CCC and minimum CSA calculations are set out in this section. The cable must also comply with the following requirements:

- A temperature and durability rating relative to the environment in which the cable will be installed. For example, if the cabling is exposed, it should be UV-resistant material or housed in UV-resistant conduit.
- Insulated or enclosed as required.

REMEMBER

According to the CEC guidelines, the maximum voltage drop between the inverter and the switchboard should be 1%.

AC Inverter Cable: Calculating the Required CCC

The AC inverter cable connects the inverter and the switchboard (or distribution board). Therefore, the CCC of the AC cables must be greater than the maximum AC output current from the inverter.

The AC cable should also be able to carry any fault current from the grid, such as a fault on the AC cable between the inverter and the switchboard. This fault current is limited by the circuit breaker at the switchboard and so the CCC of the AC cable should be greater than or equal to the rating of this circuit breaker.

AC Inverter Cable: Calculating the Minimum CSA

To keep the voltage rise below the maximum permitted, the minimum CSA should be calculated for the AC inverter cable. As mentioned in Section 14.1.2, the AC inverter cable is usually as short as possible, which will reduce the size of the CSA required.

The minimum CSA of a single phase AC cable is calculated by adjusting the formula given in Section 14.1.2:

$$V_C = \frac{1{,}000 \times Loss \times V_{AC}}{L \times I}$$

Where:

- V_C = Millivolt drop per amp-metre route length (in mV/Am)
- ***Loss*** = Maximum voltage drop in the cable (dimensionless, i.e. 5% = 0.05)
- V_{AC} = AC voltage of the grid (in V)
- L = Route length (in m)
- I = Current flow through the cable (in A)

Many AC cable manufacturers provide tables specifying the voltage drop/rise per metre of AC cable for various currents.

> ***AUSTRALIAN STANDARDS***
> ***AS/NZS 4509.2:2010*** includes tables outlining the voltage drop per ampere per metre of AC cables for various cable sizes.

EXAMPLE:
The inverter for use with a 2 kWp PV array is to be installed so that the AC cabling route will be 30 m between the inverter and the main switchboard. What is the minimum CSA required for the AC cabling to ensure that the voltage rise will be less than 1%?
Assume the following:
Maximum inverter output current = 11 A
Single phase supply: AC voltage = 230 V_{RMS}

Using Table 14.1,

$$Maximum\ V_C = \frac{1{,}000 \times Loss \times V_{AC}}{L \times I}$$

$$= \frac{1{,}000 \times 0.01 \times 230\ \text{V}}{30\ \text{m} \times 11\ \text{A}}$$

$$= 6.97\ \text{mV/Am}\ (\textit{single-phase AC})$$

Converting to three-phase:

$$\frac{6.97\ \text{mV/Am}}{1.155} = 6.03\ \text{mV/Am}\ (\textit{three-phase AC})$$

Assuming the selected cable may operate up to its rated insulation temperature of 90°C, the minimum conductor CSA that meets the calculated V_C requirement is a 10mm² cable.

14.3.2 Voltage Rise at the Inverter

The AC connection between the inverter and the electricity grid is made up of multiple cable runs: the inverter to the switchboard, the switchboard to the point of attachment, and the point of attachment to the grid. The voltage rise along this cable run, between the inverter and the grid, results in a voltage rise at the AC output of the inverter (Figure 14.5).

AUSTRALIAN STANDARDS

According to ***AS/NZS 4777.1:2016***, the overall voltage rise from the point of supply to the inverter a.c. terminals (grid-interactive port) shall not exceed 2% of the nominal voltage at the point of supply.

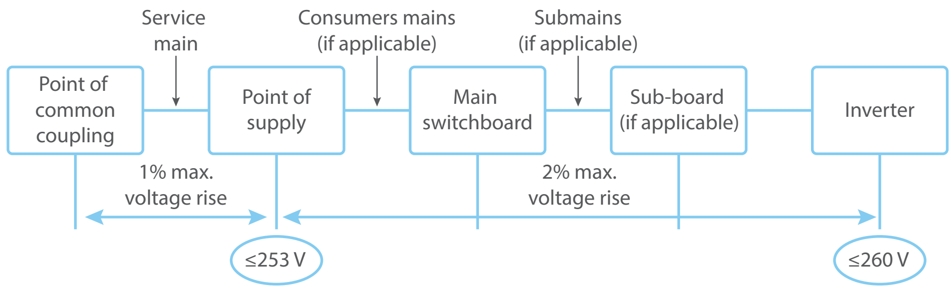


Figure 14.5: Voltage rise between the inverter and point of attachment to the grid.

If the voltage rise at the AC output of an inverter is excessive, this can cause the inverter to trip (i.e. disconnect): this happens when the inverter finds that the grid voltage is outside of the required parameters. (Figure 14.6).

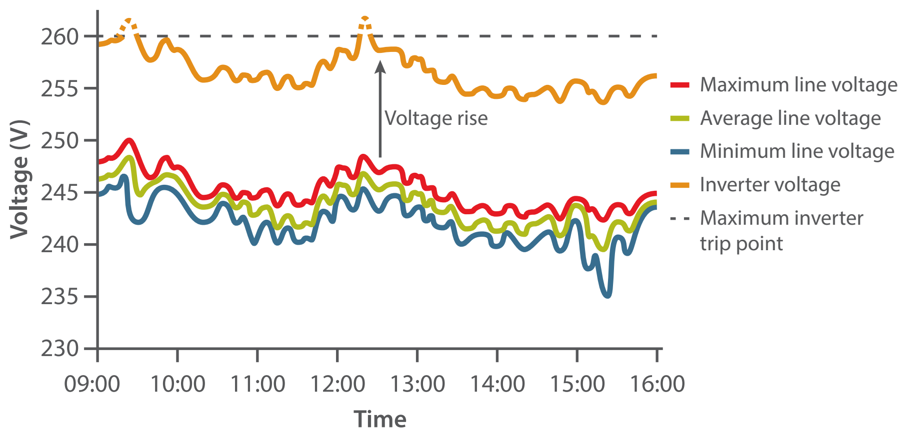


Figure 14.6: Example of recorded inverter voltage readings compared with the grid; the voltage rise between the grid and inverter is shown causing the inverter to exceed its maximum trip point twice, thus causing a false trip.

Grid voltage tolerance tripping is more likely to occur in areas where the grid voltage regularly sits at its upper voltage limit. In these areas, there does not need to be a large voltage rise at the inverter to cause the grid voltage to exceed its voltage limits and trip. Voltage rise is also generally more of a problem in large systems, in which significant cable losses can result in a high voltage rise.

If tripping caused by voltage rise will be an issue for a grid-connected PV system, there are three main options that can be explored:

1. ***Reduce the voltage rise:*** By reducing the resistance in the cable run between the inverter and the point of attachment to the grid, the voltage rise at the inverter may be reduced. This could be achieved by increasing the conductor CSA or by reducing the length of the cable run (i.e. locating the inverter closer to the

point of attachment to the grid), or it could mean replacing the main supply cables between the switchboard and the grid connection point. The resistance presented by the grid in this scenario is also responsible for voltage rise, but this issue cannot be rectified by the system designer and could require discussions with the local network provider.

2. ***Increase the inverter voltage limits:*** Some inverters may allow the voltage limit to be increased so that the inverter will not trip due to voltage rise. It is possible that the inverter's higher voltage set points for a 230V AC grid be adjusted from 260 V to 265 V AC. Inverter adjustments as outlined would need authorisation from the inverter manufacturer and network provider.
3. ***Use an inverter designed to 'ride through' grid fluctuations:*** Some inverters may have the ability to ride through brief fluctuations in the grid voltage; this can even promote better stability in the grid. This type of inverter could be beneficial for a PV system connected to a grid that has regular voltage excursions.

NOTE

If voltage rise is identified as being due to the system being located near a transformer where the voltage settings are at their upper limit, solutions 1 and 2 might be the only options.

14.3 AC Cable Design

The AC cables on a grid-connected PV system are used between the inverter and the grid connection point. The AC cable design for a grid-connected PV system will relate to the cables between the inverter and the switchboard (or the distribution board if applicable). However, potential voltage rise at the inverter could require a reassessment of the suitability of the wiring between the switchboard (or distribution board) and the grid connection point.

AUSTRALIAN STANDARDS

AS/NZS 3008.1.1:2017 states the DC and AC de-rated CCC for different cables.

AS/NZS 4777.1:2016 outlines the AC cable requirements in a grid-connected PV system.

14.3.1 AC Inverter Cable

The AC inverter cable connects the inverter to the main electrical supply. This is usually at the switchboard, but some installations might connect the inverter to the nearest distribution board. For example, an array installed on a shed roof could be connected to the grid via the shed distribution board. As outlined in Section 11.6, the nearest distribution board may be used only if the PV system has a net metering arrangement.

The voltage rating of the AC inverter cable will be the same as that for standard building cables, around 230 V_{RMS}. The required CCC and minimum CSA calculations are set out in this section. The cable must also comply with the following requirements:

- A temperature and durability rating relative to the environment in which the cable will be installed. For example, if the cabling is exposed, it should be UV-resistant material or housed in UV-resistant conduit.
- Insulated or enclosed as required.

REMEMBER

According to the CEC guidelines, the maximum voltage drop between the inverter and the switchboard should be 1%.

AC Inverter Cable: Calculating the Required CCC

The AC inverter cable connects the inverter and the switchboard (or distribution board). Therefore, the CCC of the AC cables must be greater than the maximum AC output current from the inverter.

The AC cable should also be able to carry any fault current from the grid, such as a fault on the AC cable between the inverter and the switchboard. This fault current is limited by the circuit breaker at the switchboard and so the CCC of the AC cable should be greater than or equal to the rating of this circuit breaker.

AC Inverter Cable: Calculating the Minimum CSA

To keep the voltage rise below the maximum permitted, the minimum CSA should be calculated for the AC inverter cable. As mentioned in Section 14.1.2, the AC inverter cable is usually as short as possible, which will reduce the size of the CSA required.

The minimum CSA of a single phase AC cable is calculated by adjusting the formula given in Section 14.1.2:

$$V_C = \frac{1{,}000 \times Loss \times V_{AC}}{L \times I}$$

Where:

- V_C = Millivolt drop per amp-metre route length (in mV/Am)
- $Loss$ = Maximum voltage drop in the cable (dimensionless, i.e. 5% = 0.05)
- V_{AC} = AC voltage of the grid (in V)
- L = Route length (in m)
- I = Current flow through the cable (in A)

Many AC cable manufacturers provide tables specifying the voltage drop/rise per metre of AC cable for various currents.

AUSTRALIAN STANDARDS
AS/NZS 4509.2:2010 includes tables outlining the voltage drop per ampere per metre of AC cables for various cable sizes.

EXAMPLE:
The inverter for use with a 2 kWp PV array is to be installed so that the AC cabling route will be 30 m between the inverter and the main switchboard.
What is the minimum CSA required for the AC cabling to ensure that the voltage rise will be less than 1%?
Assume the following:
Maximum inverter output current = 11 A
Single phase supply: AC voltage = 230 V_{RMS}

Using Table 14.1,

$$\begin{aligned} Maximum\ V_C &= \frac{1{,}000 \times Loss \times V_{AC}}{L \times I} \\ &= \frac{1{,}000 \times 0.01 \times 230\ \text{V}}{30\ \text{m} \times 11\ \text{A}} \\ &= 6.97\ \text{mV/Am}\ (\textit{single-phase AC}) \end{aligned}$$

Converting to three-phase:

$$\frac{6.97\ \text{mV/Am}}{1.155} = 6.03\ \text{mV/Am}\ (\textit{three-phase AC})$$

Assuming the selected cable may operate up to its rated insulation temperature of 90°C, the minimum conductor CSA that meets the calculated V_C requirement is a 10mm² cable.

It is important that the temperature coefficient quoted on the module manufacturer's data sheet is used. Typical open circuit temperature coefficient figures are quoted below in Table 15.2.

Table 15.2: *Sample temperature coefficients for different PV modules.*

Module Type	Typical Power Temperature Coefficient (γ)
Monocrystalline modules	–0.4%/°C
Polycrystalline modules	–0.4 to –0.5%/°C
Thin-film modules	–0.1 to –0.3%/°C (technology-specific)

Temperature de-rating is based on the average effective cell temperature, and not the ambient temperature. The average cell temperature will be higher than the ambient temperature because the material behind the glass on the front of the module will heat up as the solar cell absorbs sunlight throughout day. The average effective cell temperature is approximately 25°C above the ambient temperature:

$$T_{\text{CELL EFF}} = T_{\text{AMB}} + T_{\text{r}}$$

Where:

- $T_{\text{CELL EFF}}$ = effective cell temperature, in °C.
- T_{AMB} = ambient temperature, in °C.
- T_{r} = temperature rise dependent on the mounting type, in °C.

AUSTRALIAN STANDARDS

According to ***AS/NZS 5033:2014***,

T_r is expected to be approximately 25°C with very good ventilation. However, the CEC design guidelines recommend the following temperature rise values for different mounting arrangements:

- 35°C when parallel to the roof with less than 150mm standoff
- 30°C when using a rack-type mount with more than 150mm standoff
- 25°C for freestanding frames and where there is a 20 degree or greater angle between the modules and the roof

The parameter f_{TEMP} is used to represent the de-rating of the PV module adjusted for the operating temperature conditions. It can be expressed in the following formula:

$$f_{\text{TEMP}} = 1 + [\gamma \times (T_{\text{CELL EFF}} - T_{\text{STC}})]$$

Where:

- f_{TEMP} = temperature de-rating factor, dimensionless.
- γ = negative power temperature coefficient, in %/°C (decimal value).
- $T_{\text{CELL EFF}}$ = average daily cell temperature, in °C.
- T_{STC} = temperature at STC, in °C (i.e. 25°C).

Question

Calculate the efficiency (f_{TEMP}) for a 175 Wp poly-crystalline module at an ambient temperature is 23°C. The temperature coefficient for this particular module is –0.5%/°C (or in absolute terms, –0.005/°C). Assume T_r = 25°C.

Answer

The steps for calculating f_{TEMP} are as follows:
Calculate the cell temperature:

$$\begin{aligned} T_{\text{CELL EFF}} &= T_{\text{AMB}} + T_r \\ &= 23^\circ\text{C} + 25^\circ\text{C} \\ &= 48^\circ\text{C} \end{aligned}$$

Calculate the difference between the cell temperature and STC (25°C):

$$\begin{aligned} &= 48^\circ\text{C} - 25^\circ\text{C} \\ &= 23^\circ\text{C} \end{aligned}$$

Calculate the loss due to the temperature of the PV module. This is achieved by multiplying the temperature coefficient by the number of degrees the cell temperature is over STC (25°C):

$$\begin{aligned} &= -0.005/^\circ\text{C} \times 23^\circ\text{C} \\ &= -0.115 \end{aligned}$$

Convert this loss into an efficiency (loss + efficiency = 1)

$$\begin{aligned} f_{\text{TEMP}} &= 1 + -0.115 \\ &= 0.885 \\ &= 88.5\% \end{aligned}$$

Therefore, the resulting efficiency is 88.5% (or a loss of 11.5%) at an ambient temperature of 23°C.
The f_{TEMP} formula combines steps 2–4:

$$\begin{aligned} f_{\text{TEMP}} &= 1 + [y \times (T_{\text{CELL EFF}} - T_{\text{STC}})] \\ &= 1 + [-0.005 \times (48 - 25)] \\ &= 88.5\% \end{aligned}$$

The temperature coefficient may also be expressed in W/°C. If this is the case, the temperature coefficient should be converted to a percentage to calculate the efficiency, using the wattage of the module.

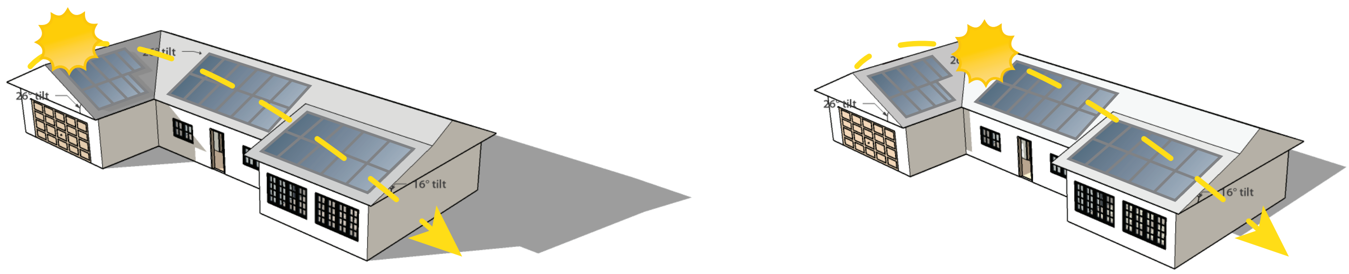


Figure 15.6: This solar array has been installed at multiple tilt angles and orientations. System losses in the form of irradiation loss are due to system shading and differing solar incidence angles.

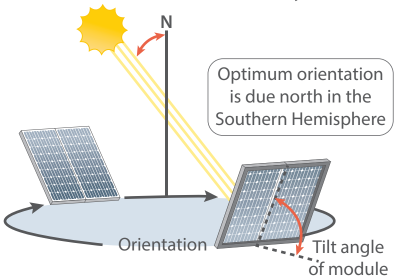


Figure 15.7: Orientation and tilt angle for solar modules.

15.1.3 Orientation and Tilt Angle of the Modules

PV modules will receive the most annual irradiation if they are tilted at an angle approximately equal to the latitude of the location and orientated towards true north for the Southern Hemisphere or true south for the Northern Hemisphere (Figure 15.7).

Modules installed at a different orientation or a non-optimal tilt angle will not produce the maximum possible annual energy output. This could be considered a system loss; however, for system yield calculations the actual available irradiation for the particular array tilt and orientation is applied. Any documentation on the system yield calculation should specify the actual irradiation value applied and it should also state, for the benefit of the system owner, what the irradiation (and system yield) would have been if the array was mounted with optimal tilt and orientation.

The calculations to determine the effect on irradiation arising from different tilts and orientations are complex. It might be worthwhile to find and use a resource able to supply irradiation data for different module tilts and orientations for a particular location.

The site assessment for a planned solar installation will identify the location where it is proposed to install the solar system. The orientation and tilt angle of the solar array is effectively tied to the proposed installation site and therefore will determine whether the tilt angle and orientation are optimum or not for the location. If they are not optimum, they will have a negative effect on the solar irradiation available at the array. The site-specific solar irradiation figure is critical to determine that solar system's performance at that given location.

When determining system yield, the array's tilt angle and orientation are applied to the available irradiation for the site. If the proposed installation will not accommodate the solar array at the optimum tilt angle and orientation, the actual loss of available irradiation must be calculated in relation to the site-specific tilt and orientation of the proposed array (see the example below).

If the proposed site dictates a non-optimum tilt angle and orientation, the reduction in the available solar irradiation is considered unavoidable. It is important that all assumptions made in relation to the effect of the prescribed tilt angle and orientation are clearly detailed for the intended client.

RESOURCE

Sources of solar irradiation data for different tilts and orientations for locations in Australia include:

- The Australian Solar Radiation Data Handbook – Exemplary Energy.
- NASA POWER Data Access Viewer (power.larc.nasa.gov/data-access-viewer).

REMEMBER

A PV module that is perpendicular to the Sun will receive the most radiation, as outlined in Section 3.3.1. As a result, tilted modules will often receive more solar radiation (>100% of the horizontal plane irradiation) in comparison to flat-mounted modules.

To calculate the annual irradiation received by the array installed with a tilt of 40° and an orientation of 50° from true north, the average monthly horizontal irradiation levels are required. The adjusted annual irradiation calculations are shown in Table 15.4.

***Table 15.4:** Annual irradiation calculations for PV modules at different tilts and orientations in Brisbane.*

Month	Days per month	Average daily irradiation on horizontal plane ($kWh/m^2/day$)	Average monthly irradiation on horizontal plane ($kWh/m^2/month$)	Percentage received by modules tilted 40° and orientated 50° (%)	Monthly irradiation received by modules tilted 40° and orientated 50° ($kWh/m^2/month$)
Jan	31	6.6	204.6	88	180.0
Feb	28	5.9	165.2	95	156.9
Mar	31	5.3	164.3	105	172.5
Apr	30	4.6	138.0	117	161.5
May	31	3.7	114.7	130	149.1
Jun	30	3.2	96.0	137	131.5
Jul	31	3.6	111.6	134	149.5
Aug	31	4.4	136.4	123	167.8
Sep	30	5.4	162.0	109	176.6
Oct	31	6.0	186.0	97	180.4
Nov	30	6.5	195.0	90	175.5
Dec	31	6.7	207.7	87	180.7
Average annual irradiation ($kWh/m^2/year$)			1881.5		1982.0

An array mounted in Brisbane with a tilt of 40° and an orientation of 50° from true north will receive an average irradiation of 1982.0 $kWh/m^2/year$, compared to 1881.5 $kWh/m^2/year$ received on a horizontal plane.

Max. inverter DC input voltage 48 V > Max. module voltage 42.56 V (at 0°C)
Min. inverter operating voltage 16 V < Min. module operating voltage 24.52 V (at 75°C)
Min. inverter start voltage 22 V < Min. module operating voltage 24.52 V (at 75°C)

However, the minimum operating voltage of the modules is not greater than the minimum operating voltage of the MPPT:

Min. peak power tracking voltage 27 V > Min. module operating voltage 24.52 V (at 75°C)

This means that for this module and inverter combination, the inverter will continue to operate but at a reduced efficiency when the cell temperature increases above a certain level. This has been calculated to be 62.2°C and would result in reduced yield on these hot days. For a real system design, different modules would be used that would always operate within the micro-inverter power point tracker range. However, for the purposes of these examples to compare multiple inverter types, this infrequent reduced efficiency will be accepted.

System Configuration

A three-phase system using Enphase M250 micro-inverters is connected as three arrays of 14 × modules/micro-inverters connected in parallel. This gives a total of 42 module/micro-inverters in each three-phase set. For an approximate 1 MWp system, there would be 80 of these three-phase sets to give a total of 80 × 42 × 300 W = 1,008,000 Wp = 1.008 MWp.

Grid Connection

The system would require the necessary cabling, distribution boards and protection equipment in order to aggregate the branch circuit power to a common connection point. This could possibly be done with 5 × 64-pole distribution boards that then feed into a main switchboard.

System yield calculations for micro-inverter systems are complex, especially if the modules are facing different orientations or have different tilt angles. The yield can be manually calculated (e.g. Table 20.1), but some micro-inverter manufacturers provide software packages to calculate the yield. As with all systems, yield calculations should also take into consideration the following: inverter efficiency, shading, accumulation of dirt, voltage drop/rise and any other known loss factors.

Sizing the String Overcurrent Protection

$$1.5 \times I_{SC\_MOD} < I_{TRIP} < 2.4 \times I_{SC\_MOD}$$

AND

$$I_{\mathrm{TRIP}} \leq I_{\mathrm{MOD\_REVERSE}}$$

Where:

- $I_{\mathrm{SC\_MOD}}$ = short circuit current of the module.
- I_{TRIP} = rated trip current of the overcurrent protection device.
- $I_{\mathrm{MOD\_REVERSE}}$ = maximum series fuse rating of the module.

Sizing the Sub-array Overcurrent Protection

$$1.25 \times I_{\mathrm{SC\_ SUB-ARRAY}} \leq I_{\mathrm{TRIP}} \leq 2.4 \times I_{\mathrm{SC\_SUB-ARRAY}}$$

Where:

- $I_{\mathrm{SC\_SUB\text{-}ARRAY}}$ = short-circuit current of the sub-array.
- I_{TRIP} = rated trip current of the fault current protection device.

Sizing the Array Overcurrent Protection

$$1.25 \times I_{\mathrm{SC\_ARRAY}} \leq I_{\mathrm{TRIP}} \leq 2.4 \times I_{\mathrm{SC\_ARRAY}}$$

Where:

- $I_{\mathrm{SC\_ARRAY}}$ = the short-circuit current of the array.
- I_{TRIP} = rated trip current of the overcurrent protection device.

Chapter 14

Calculating Voltage Drop

$$V_d = \frac{2 \times L \times I \times \rho \times cos\Phi}{A_{CABLE}}$$

Where:

- V_{d} = voltage drop in volts.
- L = route length of cable in metres (multiplying by two adjusts for total circuit wire length).
- I = current flow in amperes (for DC calculations, the I_{MP} at STC current should be used).
- ρ = resistivity of the wire in Ω/m/mm^2.
- $cos\Phi$ = power factor (include only for AC cables).
- A_{CABLE} = CSA of cable in mm^2.

Using V_C Tables to Calculate Voltage Drop

$$V_d = \frac{L \times I \times V_C}{1{,}000}$$

Where:

- V_d = voltage drop in volts.
- L = route length of cable in metres.
- I = current flow in amperes.
- V_C = millivolt drop per amp-metre route length in millivolts per amp-metre.

Calculating Voltage Drop as Percentage

$$Loss = \frac{V_d}{V_{DC}}$$

- *Loss* = voltage drop in the conductor expressed as a decimal, e.g. 3% = 0.03.
- V_d = voltage drop in volts.
- V_{DC} = system voltage in volts.

Calculating the Maximum Permitted V_C

$$V_C = \frac{1{,}000 \times Loss \times V_{DC}}{L \times I}$$

Where:

- V_C = millivolt drop per amp-metre route length in millivolts per amp-metre.
- *Loss* = maximum permissible voltage loss in the conductor, expressed as a decimal, e.g. 3% = 0.03.
- V_{DC} = system voltage in volts.
- L = route length of cable in metres.
- I = current flow in amperes.

String Cables: Calculating the Required CCC

If string overcurrent protection will be installed:

$$CCC \geq Rating\ of\ string\ overcurrent\ protection$$

If string overcurrent protection will not be installed:

$$CCC \geq I_n + (1.25 \times I_{SC\ MOD}) \times (Number\ of\ strings - 1)$$

Where:

- I_n = downstream overcurrent protection.
- *Number of strings* = total number of parallel connected strings protected by the nearest overcurrent device.

Sub-array Cables: Calculating the Required CCC

If sub-array overcurrent protection will be installed:

$$CCC \geq \textit{Rating of sub-array overcurrent protection}$$

If sub-array overcurrent protection will not be installed:

$$CCC \geq 1.25 \times \textit{sub-array short circuit current}$$

OR

$$CCC \geq I_n + (1.25 \times \textit{Sum of } I_{SC} \textit{ from other sub-arrays})$$

Where

- I_n = downstream overcurrent protection.

Array Cables: Calculating the Required CCC

1. The array short circuit current (with safety margin):

$$CCC \geq 1.25 \times \textit{array short circuit current}$$

OR

2. The inverter back-feed current:

$$CCC \geq \textit{inverter backfeed current}$$

Question 4

No.

Question 5

Voltage

Calculate the PV array maximum module voltage (i.e. at the minimum temperature):

$$V_{OC\ at\ X°C} = V_{OC\ at\ STC} + [\gamma_V \times (T_{X°C} - T_{STC})]$$

$$V_{OC\ at\ 5°C} = 44.3 + [(-0.003 \times 44.3) \times (2 - 25)]$$

$$V_{OC\ at\ 5°C} = 47.3567\ \text{V}$$

As there are seven modules in each string and voltage is the same in parallel strings, the total system voltage is:

$$PV\ array\ maximum\ voltage = 47.3567\ \text{V} \times 7$$

$$PV\ array\ maximum\ voltage = 331.49\ \text{V}$$

A maximum array voltage of 331.49 V will be used to check the suitability of the PV array DC isolator.

Current

The maximum array short circuit current is:

$$1.25 \times I_{SC}\ array = 1.25 \times 3 \times 8.1\ A = 30.375\ A$$

A maximum array current of 30.38 A will be used to check the suitability of the PV array DC isolator.

Chapter 14

Question 1

a. 3%

b. 1%

Question 2

If the current flowing through the cable exceeds the CCC of the cable, the cable can overheat. Overheating can lead to inefficiency, melted insulation, short circuit or fire.

Question 3

a. String cable:

$$Maximum\ V_C = \frac{1{,}000 \times Loss \times V_{DC}}{L \times I}$$

$$= \frac{1{,}000 \times 0.015 \times (9 \times 35.1)\ \text{V}}{14\ \text{m} \times 5.2\ \text{A}}$$

$$= 65.09\ \text{mV/Am}\ (DC)$$

Converting to three-phase:

$$\frac{65.09\ \text{mV/Am}}{1.155} = 56.35\ \text{mV/Am}\ (three\text{-}phase\ AC)$$

Assuming the selected cable may operate up to its rated insulation temperature of 90°C, the minimum conductor CSA that meets the calculated V_C requirement is a 1 mm² cable.

b. Array cable:

$$Maximum\ V_C = \frac{1{,}000 \times Loss \times V_{DC}}{L \times I}$$

$$= \frac{1{,}000 \times 0.015 \times (9 \times 35.1)\ \text{V}}{22\ \text{m} \times (4 \times 5.2\ \text{A})}$$

$$= 10.36\ \text{mV/Am}\ (DC)$$

Converting to three-phase:

$$\frac{10.36\ \text{mV/Am}}{1.155} = 8.97\ \text{mV/Am}\ (three\text{-}phase\ AC)$$

Assuming the selected cable may operate up to its rated insulation temperature of 90°C, the minimum conductor CSA that meets the calculated V_C requirement is a 6 mm² cable.

Question 4

a. Array cable:

$$V_d = \frac{L \times I \times V_C}{1{,}000}$$

$$= \frac{11\ \text{m} \times (5 \times 7.9)\ \text{A} \times (10.9 \times 1.155)\ \text{mV/Am}}{1{,}000}$$

$$= 5.47\ \text{V}$$

$$Loss = \frac{V_d}{V_{DC}}$$

$$= \frac{5.47\ \text{V}}{(10 \times 36.1)\ \text{V}}$$

$$= 0.015 \quad = 1.5\ \%$$

b. $V_{DROP\ ALLOWABLE\ STRING\ CABLE} = V_{DROP\ MAX} - V_{DROP\ ARRAY\ CABLE}$
$= 3.0\ \% - 1.5\% \quad = 1.5\%$

c. String cable:

$$Maximum\ V_C = \frac{1{,}000 \times Loss \times V_{DC}}{L \times I}$$

$$= \frac{1{,}000 \times 0.015 \times (10 \times 36.1)\ \text{V}}{20\ \text{m} \times 7.9\ \text{A}}$$

$$= 34.27\ \text{mV/Am}\ (DC)$$

Assuming the selected cable may operate up to its rated insulation temperature of 60°C, the minimum conductor CSA that meets the calculated V_C requirement is a 1.5 mm² cable.

Question 5

AC cable:

$$Maximum\ V_C = \frac{1{,}000 \times Loss \times V_{AC}}{L \times I}$$

$$= \frac{1{,}000 \times 0.01 \times 230\ \text{V}}{26\ \text{m} \times 12\ \text{A}}$$

$$= 7.37\ \text{mV/Am}\ (DC)$$

Converting to three-phase:

$$\frac{7.37\ \text{mV/Am}}{1.155} = 6.38\ \text{mV/Am}\ (three\text{-}phase\ AC)$$

Assuming the selected cable may operate up to its rated insulation temperature of 90°C, the minimum conductor CSA that meets the calculated V_C requirement is a 10 mm² cable.

$$PR = \frac{\textit{Annual average energy yield}}{\textit{Theoretical maximum energy yield}}$$

$$PR_{SYSTEM\ 1} = \frac{12{,}555\ \text{kWh}}{7\ \text{kW} \times 6.3\ \text{PSH} \times 365\ \text{days}} = 0.78$$

$$PR_{SYSTEM\ 2} = \frac{10{,}140\ \text{kWh}}{7\ \text{kW} \times 4.9\ \text{PSH} \times 365\ \text{days}} = 0.81$$

$$PR_{SYSTEM\ 3} = \frac{12{,}187\ \text{kWh}}{7\ \text{kW} \times 6\ \text{PSH} \times 365\ \text{days}} = 0.79$$

Question 6

Therefore, an array and inverter larger than 6.33 kW would be suitable. A 6.34 kW array produces 2,042.3 kWh over the 91-day billing period.

$$\textit{Reduction needed per billing period} = 5{,}540\ \text{kWh} - 3{,}500\ \text{kWh} = 2{,}040\ \text{kWh}$$

$$\textit{Reduction needed per day} = \frac{2{,}040\ \text{kWh}}{91\ \text{days}} = 22.42\ \text{kWh}$$

$$\textit{Array size} = \frac{22.42\ \text{kWh}}{4.72\ \text{PSH} \times (1 - 0.25)} = 6.33\ \text{kW}$$

Chapter 16

Question 1

- *AS/NZS 4777.1:2016*
- *AS/NZS 5033:2014*
- *AS/NZS 3000:2018*
- *AS/NZS 3008.1.1:2017*
- *AS/NZS 1768:2007*
- *AS/NZS 1170.2:2011*

Question 2

To prevent water leakage.

Question 3

To increase ventilation and to allow for debris to wash under the module.

Question 4

No, because it would void the IP rating.

Question 5

a. As the system is less than 600 V, there is no requirement for restricted access of components and conductors.

b. All systems over 600 V require restricted access that is at the least by barrier or location, where the cabling is fully enclosed such that it cannot be accessed without the use of a tool.

Question 6

a. Double-insulated, UV-resistant cabling/conduit, mechanically protected from damage if not in conduit, installed so it does not touch the roof and marked with the word 'SOLAR' every 2 m.

b. Double-insulated HD conduit, marked with the word 'SOLAR' every 2 m.

Chapter 17

Question 1

To ensure the system is reliable, performs to specification and is ready for safe operation. Commissioning records can be used in ongoing maintenance and troubleshooting and as evidence of completion.

Question 2

The correct start-up procedure is to turn on the DC switch-disconnector then the AC disconnector. This information can be found in the system documentation provided at commissioning.

Question 3

The short circuit current checks the performance of each individual module and each string of modules. This test should be done while measuring irradiance to get an accurate comparison of performance.

Question 4

Owing to the possibility that the irradiance and ambient temperature can change over the length of time taken to check 44 strings, it is recommended that one string is used as a reference string: measure its open circuit voltage at the start and, assuming this is as expected for that particular string, leave a meter on this reference string. As the V_{oc} of every other string is measured, it can be immediately compared with the voltage of the reference string.

Question 5

a. Open circuit voltage test.

b. Insulation resistance test (megger-test).

c. Short circuit current test.

Question 6

PR = Recorded system production (kWh) ÷ irradiation kWh/m² × module efficiency % × array area (m²)

$$PR = 216.133\ (\text{kWh}) \div 55.5\ (\text{kWh/m}^2) \times 0.156\ \% \times 20 \times 1.621\ (\text{m}^2)$$

$$PR = 216.133\ (\text{kWh}) \div 280.6924\ (\text{kWh})$$

$$PR = 0.7699 = 0.77$$

Therefore, this system has a PR of 77%.